Available online at www.sciencedirect.com
SCIENCE DIRECT
Renewable and Sustainable Energy Reviews
9 (2005) 592–607

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

www.elsevier.com/locate/rser

Renewable energy technologies for irrigation water pumping in India: projected levels of dissemination, energy delivery and investment requirements using available diffusion models

Pallav Purohit, Tara C. Kandpal*

Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India

Received 7 May 2004; accepted 2 July 2004

Abstract

Using the past diffusion trends of four renewable energy technologies for irrigation water pumping in India (SPV pumps, windmill pumps and biogas/producer gas driven dual fuel engine pumps), results of an attempt to project their future dissemination levels, have been presented in this study. The likely contribution of the renewable energy options considered in the study to the projected energy demand for irrigation water pumping in India has been estimated. Estimates of the associated investment requirements taking into account the learning effect have also been presented.

Keywords: Renewable energy technologies; Irrigation water pumping; Technology diffusion models

Contents

* Corresponding author. Tel.: +91 11 2659 1262; fax: +91 11 2658 2037.
E-mail address: tarak@ces.iitd.ernet.in (T.C. Kandpal).

1364-0321/$ - see front matter © 2004 Published by Elsevier Ltd.
doi:10.1016/j.rser.2004.07.002

1. Introduction

During the last two decades considerable efforts have been made in India towards large-scale diffusion of renewable energy technologies [1]. The current trend of diffusion of renewable energy technologies in India is influenced by a variety of techno-socio-economic factors including the financial and fiscal incentives provided by the central and state governments [2]. The diffusion of these technologies in future will also depend on further development and cost reduction through innovation and learning experience [3–7]. A priori knowledge of the likely diffusion of renewable energy technologies and its time variation is critically important for macro level policy interventions and planning [8–10]. In addition, for the formulation and implementation of policies in this area, issues pertaining to learning effects and returns to scale, etc. may be of considerable importance [9].

In this study a modest attempt has been made to project the future dissemination levels of renewable energy technologies for irrigation water pumping in India using four technology diffusion models namely the Bass model, Gompertz model, Logistic model and Pearl model. The likely contribution of the renewable energy options considered in the study to the projected energy demand for water pumping in India has been estimated. Estimates of the associated investment requirements taking into account the learning effect have also been presented.

2. Technology diffusion models

The diffusion of a technology measured in terms of the cumulative number of adopters usually conforms to an exponential curve [11]. The exponential growth pattern may be of three types: (i) simple exponential, (ii) modified exponential, and (iii) S-curve. Out of these three growth patterns, the simple exponential pattern is not applicable for

the dissemination of renewable energy technologies, as it would imply infinite growth. The modified exponential pattern (with a finite upper limit) is more reasonable, but such a curve may not match the growth pattern in the initial stage of diffusion [12,13]. Empirical studies have shown that in a variety of situations the growth of a technology over time may conform to an S-shaped curve, which is a combination of simple and modified exponential curves. The S-shaped curves are characterized by a slow initial growth, followed by rapid growth after a certain take-off point and then again a slow growth towards a finite upper limit to the dissemination [11]. Some of the commonly suggested technology diffusion models are briefly presented below and the same have been used in this study to estimate the cumulative number of renewable energy technologies considered in the study at different time periods.

2.1. Bass model

Bass [14] developed an empirical diffusion model in which the later adopters of a technology are influenced by earlier adopters. As per the Bass model, the cumulative number, $N(t)$, of the renewable energy technology adopted up to a particular period (tth year) can be estimated by the following expression [14]

$$N(t) = M\left[\frac{1 - e^{-(a+b)t}}{1 + \left(\frac{b}{a}\right)e^{-(a+b)t}}\right] \tag{1}$$

where M represents the estimated maximum utilization potential of the renewable energy technology in the country, a the coefficient of innovation and b the coefficient of imitation. The values of a and b can be estimated using the past data on diffusion of the technology.

2.2. Gompertz model

In this case, the cumulative number, $N(t)$, of the renewable energy technology disseminated up to the tth year can be expressed as [11]

$$N(t) = M\,e^{-a\,e^{-bt}} \tag{2}$$

This curve gives a non-symmetrical S-shaped growth pattern with an inflection point occurring at 0.367 of M [11]. Once again, the values of a and b can be determined from the past data on the diffusion of the technology.

2.3. Logistic model

As per the Logistic model, the cumulative number, $N(t)$, of the renewable energy technology disseminated up to a particular period (tth year) can be expressed as [11,15]

$$N(t) = M\left[\frac{e^{(a+bt)}}{1 + e^{(a+bt)}}\right] \tag{3}$$

where the regression coefficients a and b are estimated by a linear regression of the log–log form of Eq. (3) as given below.

$$\ln\left[\frac{\frac{N(t)}{M}}{1-\frac{N(t)}{M}}\right] = a + bt \quad (4)$$

2.4. Pearl model

As per this model, the following expression can be used for estimating the cumulative number, $N(t)$, of the renewable energy technology disseminated up to the tth year (with the coefficients a and b determined from the earlier data on the diffusion of the technology) [11]

$$N(t) = \frac{M}{1 + a\,\mathrm{e}^{-bt}} \quad (5)$$

3. Reduction in the unit cost of renewable energy technologies for irrigation water pumping due to learning effect

For many products and services, unit costs are expected to decrease with increasing experience. Unit costs are often modelled to decrease by a constant percentage called the learning rate for each doubling of experience [5–7]. The capital costs of renewable energy technologies are also expected to decrease with increased levels of their diffusion. The reductions in the costs (and prices) of renewable energy technologies can be evaluated in several ways. The cost reductions can be evaluated through a detailed assessment of the technology and an analysis of manufacturing costs as a function of technological improvements [7]. For example, by investigating the cost reductions that correspond to likely technical innovations in the various PV system components, one can arrive at estimates for their future expected cost levels [5,6].

The unit cost of a product following the learning curve can be expressed as [7]

$$C_t = C_0\left[\frac{N(t)}{N(0)}\right]^{\alpha} \quad (6)$$

where C_t represents the unit cost at time t, C_0 the unit cost at time zero, $N(t)$ the cumulative production at time t, $N(0)$ the cumulative production at time zero, and α the elasticity of unit costs with respect to cumulative production.

With every doubling of cumulative production, costs decrease to a value expressed as the initial cost multiplied by a factor called the progress ratio PR (=1−learning rate)

$$PR = 2^{\alpha} \quad (7)$$

Using the above-mentioned technology diffusion models the cumulative numbers of four renewable energy technologies for irrigation water pumping considered in this study have been estimated at different time periods along with the projections of investment requirement using learning curve effect.

4. Estimation of the energy delivered by renewable energy technologies

To estimate the primary energy delivered by renewable energy technologies for irrigation water pumping it is assumed that the energy delivered in tth year is due to the systems installed till the end of the $(t-1)$th year using the technology diffusion models discussed in Section 2 of this paper. The annual primary energy delivered (in PJ) by SPV

Table 1
Input parameters used in the diffusion of renewable energy technologies for irrigation water pumping in India

Parameter	Symbol	Unit	Value
Capacity of biogas plant	v	m^3	4
Capacity of SPV pump	P_{spv}	kW_p	1.8
Capacity of producer gas driven dual fuel engine pump	P_{bg}	hp	5
Capital cost of SPV pump	C_{spv}	Rs	340,000
Capital cost of windmill pumps	C_{wind}	Rs	45,000
Capital cost of biogas plant	C_{bp}	Rs	20,000
Capital cost of biomass gasifier	C_{bg}	Rs	50,000
Capacity utilization factor of SPV pump	CUF_{spv}	Fraction	0.20
Capacity utilization factor of producer gas driven dual fuel engine pump	CUF_{bg}	Fraction	0.25
Coefficient of performance of windmill	C_p	Fraction	0.25
Cut-in wind speed of Apoly-12-pu-500 windmill pump	v_{ci}	m/s	2.5
Cut-out wind speed of Apoly-12-pu-500 windmill pump	v_{co}	m/s	10.00
Daily average solar radiation availability	I	$kW\ h/m^2$ per day	5.5
Density of air	ρ_a	kg/m^3	1.225
Derating factor	μ	Fraction	0.1
Efficiency of pump used with the windmill	$\eta_{p,wind}$	Fraction	0.80
Efficiency of pump used with the SPV system	$\eta_{p,spv}$	Fraction	0.40
Mechanical availability factor of windmill pump	γ	Fraction	0.90
Overall efficiency of electric-motor-pumpset	$\eta_{p,emp}$	Fraction	0.52
Overall efficiency of coal based thermal power plant	η_{tpp}	Fraction	0.35
Overall transmission and distribution losses of electricity	η_{tdl}	Fraction	0.22
Potential number of SPV pumps	M_{spv}	Million	0.6
Potential number of windmill pumps	M_{wind}	Million	0.4
Potential number of biogas driven dual fuel engine pumps	M_{bp}	Million	0.4
Potential number of producer gas based dual fuel engine pumps	M_{bg}	Million	0.4
Progress ratio for SPV pumps	PR_{spv}	Fraction	0.80
Progress ratio for windmill pumps	PR_{wind}	Fraction	0.92
Progress ratio for biogas driven dual fuel engine pumps	PR_{bp}	Fraction	0.95
Progress ratio for producer driven dual fuel engine pumps	PR_{bg}	Fraction	0.90
Rated wind speed of Apoly-12-pu-500 windmill pump	v_r	m/s	5
Rotor diameter of Apoly-12-pu-500 windmill pump	–	m	5
Total energy use for irrigation as a fraction of total energy use in all operations	–	Fraction	0.32
Useful lifetime of SPV pump	t_{spv}	Years	20
Useful lifetime of windmill pump	t_{wind}	Years	15
Useful lifetime of biogas plant	t_{bp}	Years	25
Useful lifetime of biomass gasifier	t_{bg}	h	10,000

pumps in the tth year, $\mathrm{APE_{spv}}(t)$, can be estimated as [16,17]

$$\mathrm{APE_{spv}}(t)=\left(\frac{3.6\times 8760}{10^9}\right)\left[\frac{\mathrm{CUF_{spv}}P_{\mathrm{spv}}\eta_{\mathrm{p,spv}}N_{\mathrm{spv}}(t-1)}{\eta_{\mathrm{p,emp}}(1-\eta_{\mathrm{tdl}})\eta}\right] \tag{8}$$

where P_{spv} (in $\mathrm{kW_p}$) represents the capacity of SPV system, $\mathrm{CUF_{spv}}$ (in fraction) the capacity utilization factor, $\eta_{\mathrm{p,spv}}$ (in fraction) the overall efficiency of SPV water pump, $\mathrm{N_{spv}}(t-1)$ the cumulative number of SPV pumps installed to the tth period, $\eta_{\mathrm{p,emp}}$ (in fraction) the overall efficiency of electric motor pump, η_{tdl} (in fraction) the overall electrical transmission and distribution losses, and η_{tpp} (in fraction) the overall efficiency of coal thermal power plant.

Similarly, the annual primary energy delivered by windmill pumps in the tth year, $\mathrm{APE_{wind}}(t)$ (in PJ) can be estimated as [18]

$$\mathrm{APE_{wind}}(t)=\left(\frac{15.77}{10^9}\right)\left(\frac{\eta_{\mathrm{p,wind}}\gamma C_{\mathrm{p}}\rho_{\mathrm{a}}AkN_{\mathrm{wind}}(t-1)}{\eta_{\mathrm{p,emp}}(1-\eta_{\mathrm{tdl}})\eta_{\mathrm{tpp}}c^k}\right)\times\left[\int_{v_{\mathrm{ci}}}^{v_{\mathrm{r}}} v^{(k+2)}\,\mathrm{e}^{-(v/c)^k}\mathrm{d}v+v_{\mathrm{r}}^3\int_{v_{\mathrm{r}}}^{v_{\mathrm{co}}} v^k\,\mathrm{e}^{-(v/c)^k}\mathrm{d}v\right] \tag{9}$$

where $\eta_{\mathrm{p,wind}}$ (in fraction) represents the efficiency of pump used with the windmill, γ (in fraction) the mechanical availability factor of the windmill pump accounting for downtime during maintenance, etc. $N_{\mathrm{wind}}(t-1)$ the cumulative number of windmill pumps installed to the tth period, C_{p} (in fraction) the coefficient of performance of the wind rotor, ρ_{a} (in kg/m^3) the density of air, A (m^2) the swept area of the rotor, k the shape parameter, c (in m/s) the scale parameter, v (in m/s) the wind speed, v_{r} (in m/s) the rated

Table 2
Values of regression coefficients for different diffusion models

Diffusion model	Renewable energy technology for water pumping	Regression coefficients	
		a	*b*
Bass model	SPV pumps	0.000466	0.26467
	Windmill pumps	0.000203	0.20790
	Biogas driven dual fuel engine pumps	0.000032	0.60873
	Producer gas driven dual fuel engine pumps	0.000014	0.12241
Gompertz model	SPV pumps	7.9727	0.0769
	Windmill pumps	7.7597	0.0266
	Biogas driven dual fuel engine pumps	8.4784	0.0131
	Producer gas driven dual fuel engine pumps	10.9598	0.0269
Logistic model	SPV pumps	−7.91	0.50
	Windmill pumps	−8.40	0.28
	Biogas driven dual fuel engine pumps	−9.61	0.17
	Producer gas driven dual fuel engine pumps	−11.19	0.33
Pearl model	SPV pumps	2079.57	0.44
	Windmill pumps	2104.50	0.17
	Biogas driven dual fuel engine pumps	4212.12	0.09
	Producer gas driven dual fuel engine pumps	54,130.03	0.26

wind speed, v_{ci} (in m/s) the cut-in wind speed and, v_{co} (in m/s) the cut-out wind speed of the windmill.

The annual primary energy delivered by biogas driven dual fuel engine pump in the tth year, $APE_{bp}(t)$ (in PJ) can be estimated as [16]

$$APE_{bp}(t) = \left(\frac{0.746 \times 8760}{10^9}\right)\left[\frac{CUF_{bp}P_{bp}N_{bp}(t-1)(1-\mu)\eta_{dep}}{\eta_{p,emp}(1-\eta_{tdl})\eta}\right] \quad (10)$$

where CUF_{bp} (in fraction) represents the capacity utilization factor of the system (it is the fraction of time the system operates in a year), P_{bp} (hp) the capacity of the dual fuel engine pump, $\eta_{p,dep}$ (in fraction) the efficiency of dual fuel engine pump, μ (in fraction) the derating factor (it takes into account the loss in the performance of the engine in dual fuel

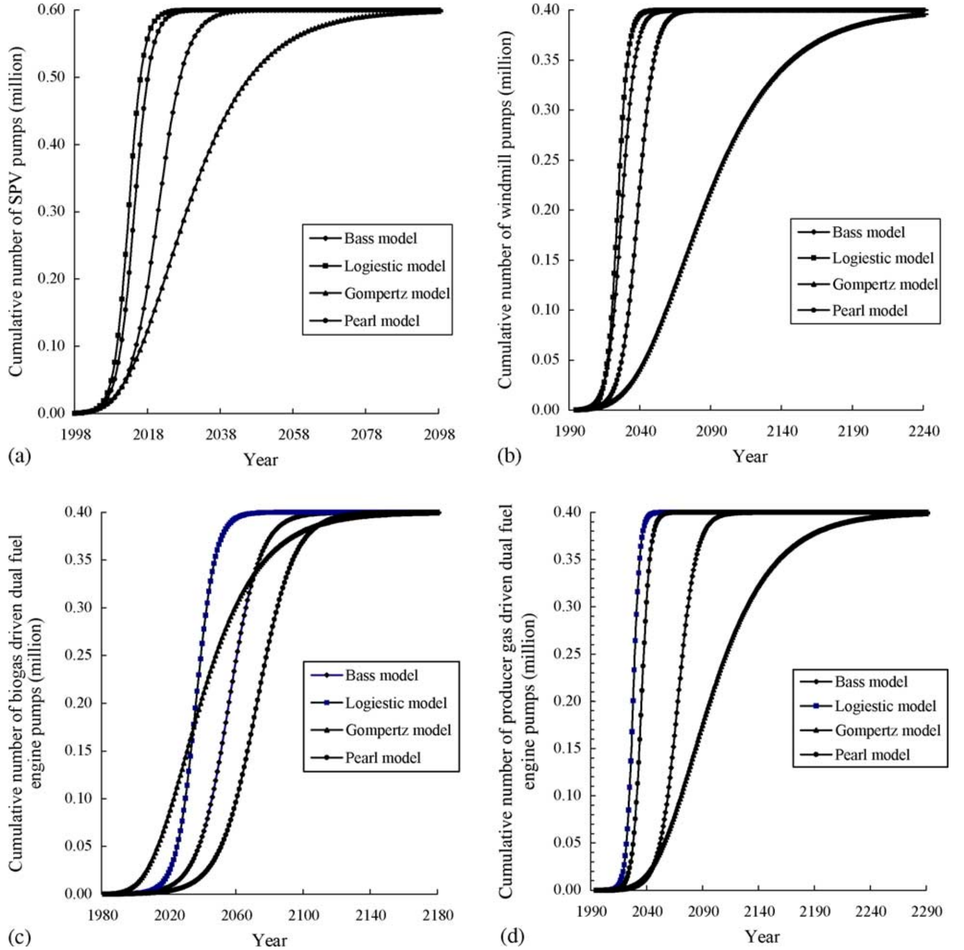


Fig. 1. Time variation of cumulative number of (a) SPV pumps ($t=1$ for 1998); (b) windmill pumps ($t=1$ for 1995); (c) biogas driven dual fuel engine pumps ($t=1$ for 1982); (d) producer gas driven dual fuel engine pumps ($t=1$ for 1995) in India.

mode) and, $N_{bp}(t-1)$ the cumulative number of biogas driven dual fuel engine pumps installed to the tth period.

Similarly, the annual primary energy delivered by producer gas driven dual fuel engine pump in the tth year, $APE_{bg}(t)$ (in PJ) can be estimated as [16]

$$APE_{bg}(t) = \left(\frac{0.746 \times 8760}{10^9}\right)\left[\frac{CUF_{bg}P_{bg}N_{bg}(t-1)(1-\mu)\eta_{dep}}{\eta_{p,emp}(1-\eta_{tdl})\eta}\right] \quad (11)$$

where CUF_{bg} (in fraction) represents the capacity utilization factor of the producer gas driven dual fuel engine pump (it is the fraction of time, the system operates in a year), P_{bg} (in hp) the capacity of the dual fuel engine pump and, $N_{bg}(t-1)$ the cumulative number of producer gas driven dual fuel engine pumps installed to the tth period.

The annual primary energy $APE(t)$ delivered by all the four renewable energy technologies for irrigation water pumping in tth year can, therefore, be estimated as the total sum of the annual energy deliveries of individual technologies using Eqs. (8)–(11).

The following time-trend relation has been recommended to express the time variation of total energy use for irrigation water pumping, TEU_{irr} (in PJ) in the agriculture sector [19].

$$TEU_{irr} = 0.32(24.27t + 91.27) \quad (12)$$

Table 3
Projected time variation of the cumulative number of renewable energy technologies for water pumping in India using technology growth models

Diffusion model	Year	Projected cumulative diffusion			
		SPV pumps	Windmill pumps	Biogas driven dual fuel engine pumps	Producer gas driven dual fuel engine pumps
Bass model	2005	7636	3435	1459	132
	2010	30,407	10,255	2589	283
	2015	102,417	15,532	4521	560
	2020	262,869	41,624	7806	1072
	2025	447,726	99,376	13,338	2011
Gompertz model	2005	8064	1222	19,677	115
	2010	31,916	2515	35,290	321
	2015	81,419	3271	56,514	786
	2020	154,035	5952	82,602	1721
	2025	237,752	10,054	112,165	3415
Logistic model	2005	11,644	1876	1729	206
	2010	116,046	7373	4101	1069
	2015	446,358	12,645	9646	5485
	2020	583,425	46,043	22,269	26,913
	2025	598,596	136,557	49,322	108,943
Pearl model	2005	9477	1245	843	132
	2010	75,404	2918	1328	490
	2015	337,688	4097	2089	1813
	2020	552,115	9508	3284	6644
	2025	594,246	21,678	5154	23,591

where $t=1$ for the year 1951. The term inside the bracket of the right hand side of Eq. (12) is the total energy use in the agriculture sector. The average value of the total energy use for irrigation water pumping as a fraction of the total energy use in the agriculture sector has been estimated to be 0.32 using the data given in Moulik et al. [20].

5. Results and discussion

Table 1 presents the values of different input parameters used in projecting the time trend of the dissemination of the four renewable energy technologies for irrigation water pumping in India [1,16–18,21–25]. The values of the coefficient of innovation and the coefficient of imitation using Bass model have been estimated by regression of the time series data for the installation of renewable energy technologies extracted from the annual reports of the Ministry of Non-Conventional Energy Sources of the Government of India [1]. Table 2 presents the estimated values of the coefficient of innovation and coefficient of imitation for the four renewable energy technologies for irrigation water pumping using Bass model. It may be noted that the effect of imitators is higher in case of biogas driven dual fuel engine pumps followed by SPV pumps, windmill pumps and producer gas driven dual fuel engine pumps in this order. The values of the regression coefficients for

Table 4
Learning curve effect on the capital cost of renewable energy technologies for irrigation water pumping

Renewable energy technology	Year[a]	Projected capital cost with learning effect			
		Bass model	Logistic model	Gompertz model	Pearl model
SPV pump (capacity = 1.8 kW_p)	2005	233,802	210,383	237,211	223,457
	2010	145,445	96,623	152,337	114,611
	2015	96,221	53,244	112,686	70,731
	2020	68,119	44,102	91,776	60,378
	2025	54,349	43,149	79,808	58,965
Windmill pump (type = Apoly-12-PU-500)	2005	40,744	40,838	42,334	42,376
	2010	35,518	34,756	38,631	38,345
	2015	31,370	29,642	35,656	34,711
	2020	27,949	25,477	33,240	31,450
	2025	25,240	22,430	31,260	28,555
Biogas driven dual fuel engine pump (capacity = 4 m^3)	2005	19,480	19,245	19,394	19,600
	2010	18,670	18,054	18,573	18,953
	2015	17,915	16,946	17,937	18,327
	2020	17,206	15,929	17,440	17,724
	2025	16,537	15,019	17,050	17,143
Producer gas driven dual fuel engine pump (capacity = 5 hp)	2005	45,840	43,030	44,929	44,365
	2010	40,676	33,510	38,281	36,353
	2015	36,599	26,123	33,281	29,795
	2020	33,139	20,465	29,447	24,446
	2025	30,102	16,395	26,459	20,133

[a] $t=1$ for the year 2002.

Gompertz model, Logistic model and Pearl model, respectively, are also presented in the same table. Fig. 1(a)–(d), respectively, represents the projected time variation of the cumulative number of SPV pumps, windmill pumps, biogas and producer gas driven dual fuel engine pumps using the four technology diffusion models considered in the study. From these figures it may be noted that in the case of the Logistic model the maximum utilization potential of renewable energy technologies is achieved the fastest (optimistic scenario), whereas the diffusion following the Gompertz model is the slowest (pessimistic scenario). The other two technology diffusion models (viz. Bass model and Pearl model)

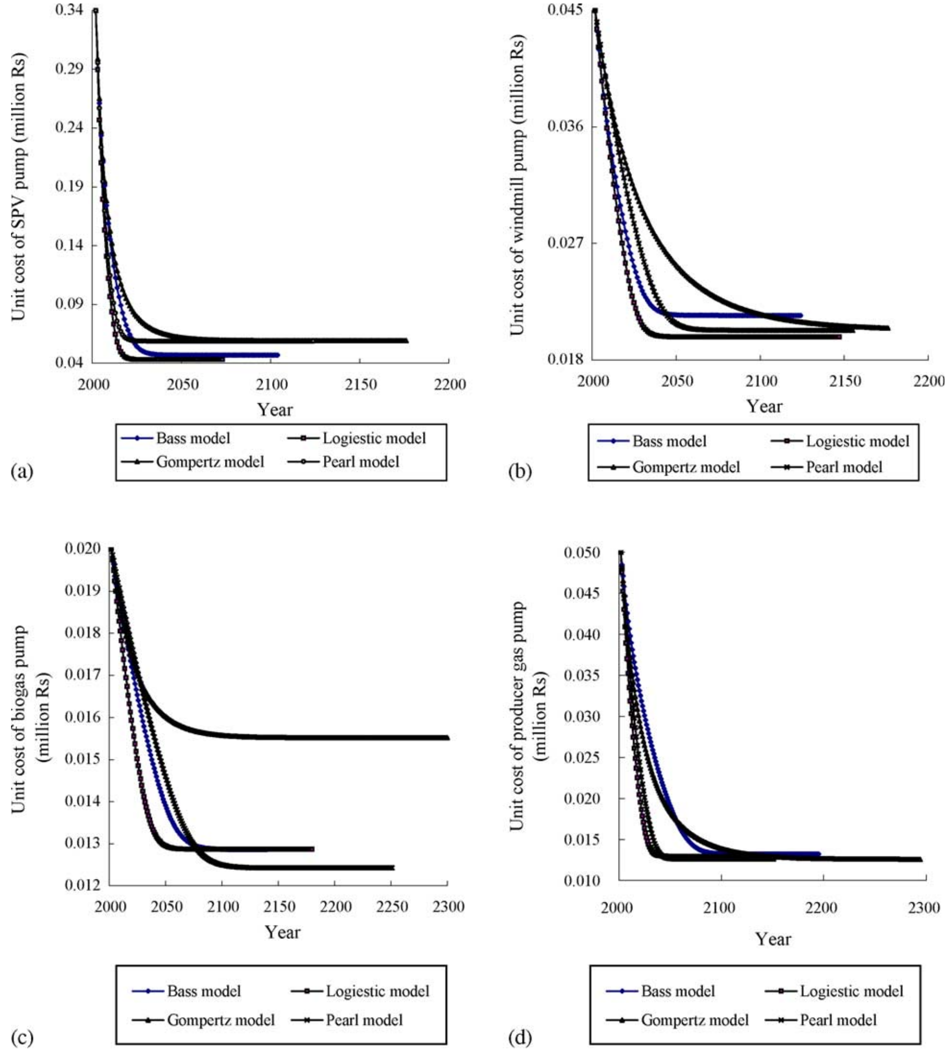


Fig. 2. Learning effect on the unit cost of different renewable energy technologies for irrigation water pumping using several technology growth models. (a) SPV pumps; (b) windmill pumps; (c) biogas driven dual fuel engine pumps; (d) producer gas driven dual fuel engine pumps.

represent an intermediate trend of diffusion of renewable energy technologies for irrigation water pumping. Table 3 presents the time variation of the projected cumulative number of renewable energy technologies for water pumping using the above four technology diffusion models as discussed in Section 2. Results of this study indicate that in India, even with highly favourable assumptions, the dissemination of renewable energy technologies for irrigation water pumping is not likely to reach its maximum estimated potential in another 25 years.

The progress ratio for the decline in cost is based on historic data for technologies, which emerged, were commercialised, and matured in the past [4]. Typical values of the progress ratio range from 70 to 90% (i.e. PR varying from 0.7 to 0.9), although the values have also been observed falling outside this range [7]. A progress ratio of 80% is often used to estimate future cost reduction potential for a variety of energy technologies [4]. The values of the progress ratio for SPV pumps has been taken to be 80% [6,7]. Ibenholt [5] has estimated experience curve for cost per kW h electricity generated by wind for

Table 5
Capital investment requirement in (million Rs[a]) with learning curve effect on renewable energy technologies for irrigation water pumping

Diffusion model	Year	SPV pumps		Windmill pumps		Biogas driven dual fuel engine pumps		Producer gas driven dual fuel engine pumps	
		Incremental numbers installed	Capital investment (million Rs)	Incremental numbers installed	Capital investment (million Rs)	Incremental numbers installed	Capital investment (million Rs)	Incremental numbers installed	Capital investment (million Rs)
Bass model	2005	2002	468.00	713	29.07	162	3.15	21	0.94
	2010	7030	1022.42	1957	41.95	277	5.17	38	1.54
	2015	20,783	1999.74	5080	159.37	473	8.47	70	2.56
	2020	38,404	2616.05	11,470	320.56	802	13.80	129	4.26
	2025	32,053	1742.06	19,145	483.21	1345	22.24	236	7.10
Gompertz model	2005	2350	557.46	177	7.48	2446	47.43	23	1.03
	2010	6672	1016.37	321	12.41	3580	66.50	57	2.17
	2015	12,014	1353.86	533	19.02	4669	83.75	123	4.09
	2020	15,865	1455.99	818	27.18	5547	96.73	237	6.99
	2025	16,958	1353.35	1169	36.54	6112	104.20	416	11.00
Logistic model	2005	4520	950.86	452	18.44	275	5.29	58	2.49
	2010	39,790	3844.60	1756	61.03	649	11.72	299	10.03
	2015	63,433	3377.41	6366	188.69	1508	25.56	1524	39.80
	2020	10,243	451.76	18,100	461.14	3387	53.95	7179	146.91
	2025	905	39.03	27,598	619.02	7041	105.74	24,082	394.82
Pearl model	2005	3330	744.04	195	8.28	73	1.44	30	1.35
	2010	24,496	2807.47	456	17.49	115	2.18	113	4.11
	2015	65,491	4632.24	1054	36.59	181	3.32	417	12.41
	2020	23,229	1402.54	2379	74.81	284	5.03	1513	36.98
	2025	3120	183.97	5088	145.29	443	7.60	5191	104.52

[a] 1US$ = Rs 45.39 on 10 October 2003.

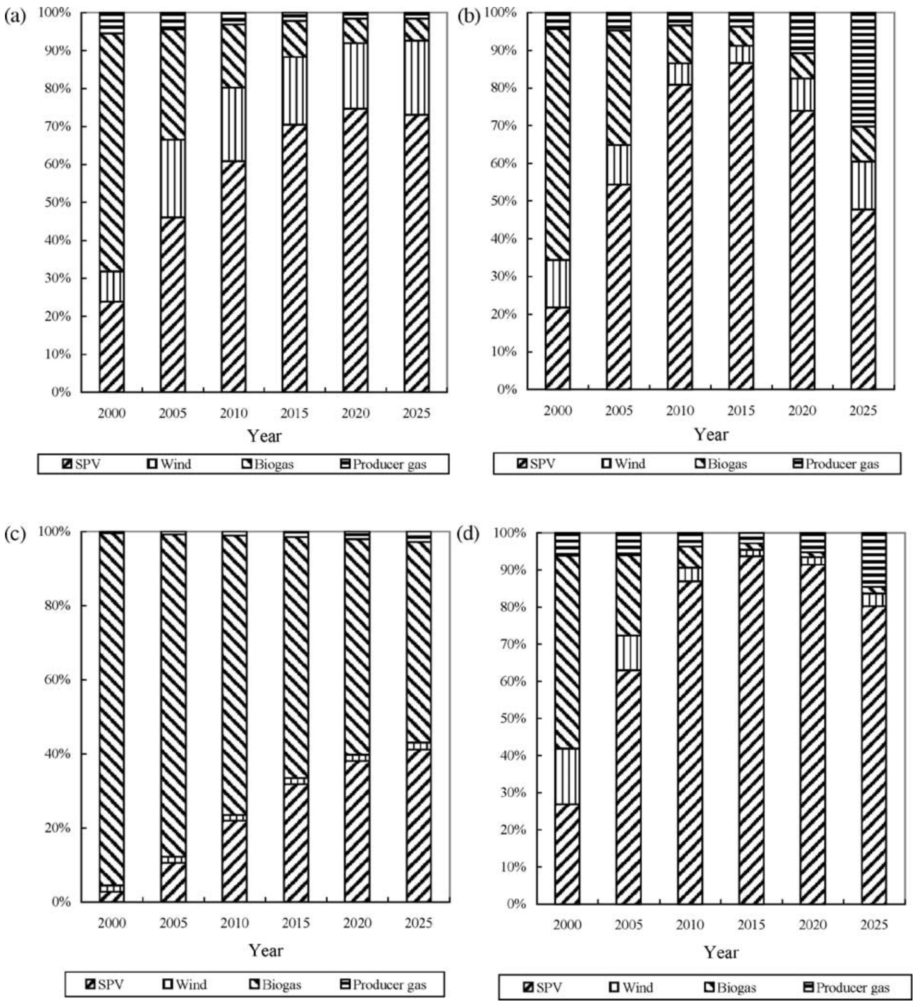


Fig. 3. Projections of energy delivered (in PJ) by renewable energy technologies for irrigation water pumping using several technology growth models. (a) Bass model; (b) Logistic model; (c) Gompertz model; (d) Pearl model.

the period, 1984–1999 with a progress ratio of 92.2%. Since, such data for India is not yet available, above value of progress ratio has been used to analyse the learning curve effect on the unit cost of windmill pumps for irrigation water pumping in India. The progress ratio for biogas driven dual fuel engine pumps has been taken to be 95%. Despite the fact that producer gas driven dual fuel engine pumps are relatively new in the learning curve, a progress ratio of 90% has been taken in this study. Table 4 presents the learning effect in terms of the reduction in the cost of the four technologies at different time periods. With the chosen values of input parameters the learning effect appears to be quite substantial in

case of SPV pumps as shown in Fig. 2. Table 5 presents the corresponding capital investment requirement for the dissemination of renewable energy technologies for irrigation water pumping.

Using estimated cumulative number of installations of renewable energy technologies for irrigation water pumping at different points of time, the primary energy delivered by these systems has been estimated using Eqs. (8)–(11). The 1.8 kW_p capacity SPV pump so far being the most prevalent size in India [1], the same have been considered in the estimation of primary energy delivered by SPV pump using Eq. (8). To estimate the primary energy delivered by windmill pumps, the APOLY-12-PU-500 windmill pump located at Indore (an offshore site with good wind resource) has been selected. To estimate the primary energy delivered by biogas driven dual fuel engine pump, a 4 m^3 biogas plant has been considered. Similarly, a 5 hp capacity producer gas driven dual fuel engine pump has been selected to estimate the primary energy delivered by the system. Fig. 3 presents the projected time variation of the primary energy delivered by renewable energy technologies for irrigation water pumping. The corresponding values of the primary energy delivered by renewable energy technologies for irrigation water pumping are presented in Table 6. It may be noted that in the long run SPV pumps are expected to contribute a major fraction of

Table 6
Primary energy delivered by renewable energy technologies for irrigation water pumping in India

Diffusion model	Year	Annual primary energy delivered (PJ)			
		SPV pumps	Windmill pumps	Biogas driven dual fuel engine pumps	Producer gas driven dual fuel engine pumps
Bass model	2005	180.23	80.06	113.75	17.41
	2010	747.83	238.98	202.75	39.40
	2015	2611.39	660.57	355.02	79.94
	2020	7180.47	1666.42	614.22	154.60
	2025	13,297.02	3560.39	1051.74	291.90
Gompertz model	2005	182.80	28.49	1511.07	13.67
	2010	807.53	58.61	2780.79	40.33
	2015	2220.20	110.21	4546.50	103.86
	2020	4419.95	191.57	6757.36	237.49
	2025	7063.03	310.82	9300.34	489.42
Logistic model	2005	227.92	43.72	127.52	19.93
	2010	2439.38	171.81	302.71	103.27
	2015	12,249.47	648.93	713.64	532.77
	2020	18,335.60	2140.99	1655.86	2684.10
	2025	19,119.67	5061.51	3707.87	12,102.61
Pearl model	2005	196.65	29.02	67.51	18.96
	2010	1628.51	67.99	106.32	70.32
	2015	8707.38	158.44	167.34	260.25
	2020	16,918.61	364.47	263.13	956.62
	2025	18,909.62	814.57	413.09	3430.32

Table 7
Fuel mix for irrigation water pumping using technology diffusion models for the installation of renewable energy technologies

Diffusion model	Year	Primary energy delivered						
		TEU_{irr} (PJ)	Renewables		Diesel		Electricity	
			Amount (PJ)	% of total	Amount (PJ)	% of total	Amount (PJ)	% of total
Bass model	2005	450	0.39	0.09	215.84	47.96	233.83	51.95
	2010	489	1.23	0.25	234.16	47.88	253.68	51.87
	2015	528	3.71	0.70	251.70	47.66	272.67	51.63
	2020	567	9.62	1.70	267.59	47.19	289.89	51.12
	2025	606	18.20	3.00	282.19	46.56	305.71	50.44
Gompertz model	2005	450	1.74	0.39	215.20	47.81	233.13	51.80
	2010	489	3.69	0.75	232.98	47.64	252.40	51.61
	2015	528	6.98	1.32	250.13	47.37	270.97	51.31
	2020	567	11.61	2.05	266.63	47.02	288.85	50.94
	2025	606	17.16	2.83	282.69	46.64	306.25	50.53
Logistic model	2005	450	0.42	0.09	215.83	47.96	233.81	51.95
	2010	489	3.02	0.62	233.31	47.70	252.75	51.68
	2015	528	14.14	2.68	246.69	46.71	267.25	50.61
	2020	567	24.82	4.38	260.29	45.90	281.98	49.72
	2025	606	39.99	6.60	271.73	44.83	294.38	48.57
Pearl model	2005	450	0.31	0.07	215.88	47.97	233.87	51.96
	2010	489	1.87	0.38	233.85	47.82	253.34	51.80
	2015	528	9.29	1.76	249.02	47.16	269.77	51.08
	2020	567	18.50	3.26	263.32	46.43	285.26	50.30
	2025	606	23.57	3.89	279.61	46.13	302.92	49.98

primary energy requirement for irrigation water pumping followed by biogas driven dual fuel engine pumps, windmill pumps and producer gas driven dual fuel engine pumps in the order of their contributions (Fig. 3).

Using the data given in Moulik et al. [20] the time variation of total energy use for irrigation water pumping (TEU_{irr}) has been estimated and presented in Table 7. The average value of the energy consumption for irrigation water pumping as a fraction of the total energy use in the agriculture sector has been estimated at about 0.32 and the same is assumed to be constant with time. (It may, however, be noted that simple time trend analysis used in this work due to unavailability of data have limited utility for long term forecasting of energy demand in agriculture.) The projections of fuel mix for irrigation water pumping in India using the four technology diffusion models for the cumulative number of installations of renewable energy technologies are also presented in Table 7. It may be noted that in the Logistic model the contribution of renewable energy technologies in the fuel mix for irrigation water pumping will be 6.6% up to the year 2025, whereas in the Gompertz model the same will contribute 2.83% of the total energy demand for irrigation water pumping. Electricity and diesel pumps will still be the major

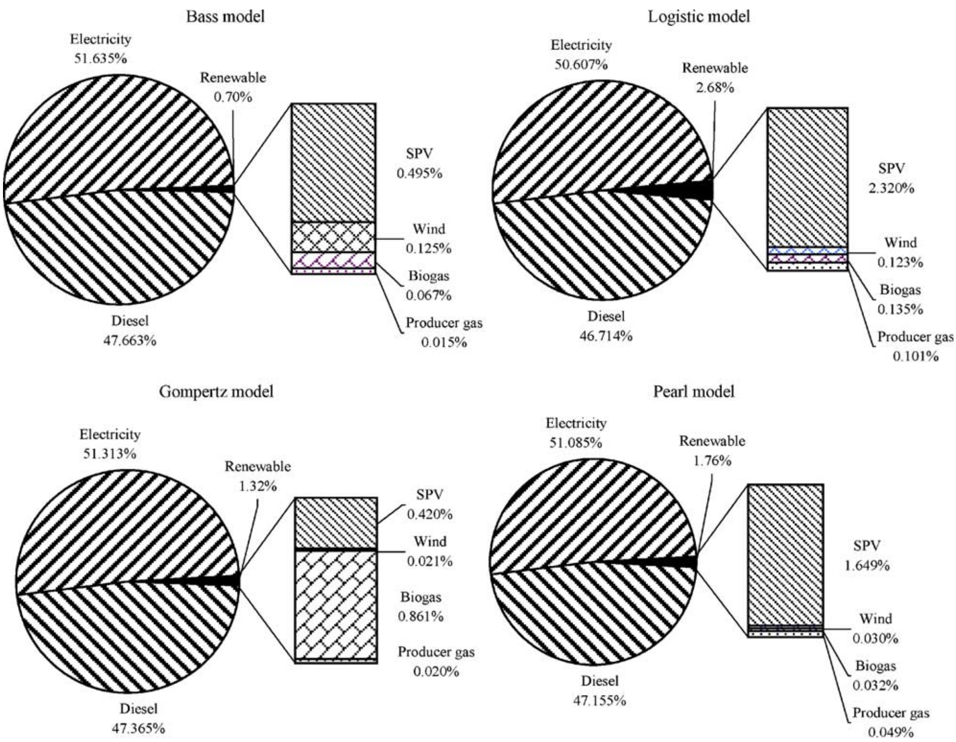


Fig. 4. Fuel mix for irrigation water pumping in the year 2015.

contributors for meeting the irrigation energy requirement for irrigation water pumping. Fig. 4 presents the fuel mix for irrigation water pumping in the year 2015 for the four technology diffusion models. It may be noted that, for the year 2015, the primary energy delivered by renewable energy technologies for irrigation water pumping will be the highest (at about 2.68% of the total primary energy demand) for the Logistic model followed by Pearl model (1.76%), Gompertz model (1.32%) and Bass model (0.70%), respectively. Amongst different renewable energy technologies SPV pump is expected to contribute a major fraction of this figure.

6. Concluding remarks

Though the projected levels of dissemination of the four renewable energy technologies for irrigation water pumping using available technology diffusion models appear to be on the optimistic side (as against the reported existing levels of diffusion) their contribution to the overall energy supply mix is rather small. On the other hand, a substantial amount of investment is required even to achieve this level of dissemination.

Acknowledgements

The financial assistance provided by the Council of Scientific and Industrial Research (CSIR), New Delhi to the first author (Pallav Purohit) is gratefully acknowledged.

References

[1] MNES. Annual report: 2002–03. New Delhi: Ministry of Non-Conventional Energy Sources (MNES), Government of India; 2003.
[2] MNES. Renewable energy in India: business opportunities. New Delhi: Ministry of Non-Conventional Energy Sources, Government of India; 2001.
[3] Mackay RM, Probert SD. Likely market penetrations of renewable energy technologies. Appl Energy 1998; 59:1–38.
[4] Grubler A, Nakienovi N, Victor DG. Dynamics of energy technologies and global change. Energy Policy 1999;27:247–80.
[5] Ibenholt K. Explaining learning curves for wind power. Energy Policy 2002;30:1181–9.
[6] Masini A, Frankl P. Forecasting the diffusion of photovoltaic systems in southern Europe: a learning curve approach. Technol Forecasting Social Change 2003;70:39–65.
[7] Zwaan BVD, Rabl A. Prospects for PV: a learning curve analysis. Sol Energy 2003;74:19–31.
[8] Islam T, Meade N. The diffusion of successive generations of a technology: a more general model. Technol Forecasting Social Change 1997;56:49–60.
[9] Isoard S, Soria A. Technical change dynamics: evidence from the emerging renewable energy technologies. Energy Econ 2001;23:619–36.
[10] Albright RE. What can past technology forecasts tell us about the future? Technol Forecasting Social Change 2002;69:443–64.
[11] Islam MN, Haque MM. Technology, planning and control. Dhaka: World University Service Press; 1994.
[12] Ang BW, Ng TT. The use of growth curves in energy studies. Energy 1992;17:25–36.
[13] Martino JP. A review of selected recent advances in technological forecasting. Technol Forecasting Social Change 2003;70:719–33.
[14] Bass F. A new product growth model for consumer durables. Manage Sci 1969;15:215–27.
[15] Loulou R, Shukla PR, Kanudia A. Energy and environmental policies for a sustainable future: analysis with the Indian MARKAL model. New Delhi: Allied Publishers; 1997.
[16] Kandpal TC, Purohit P, Kumar A, Chandrasekar B. Economics of renewable energy utilization in developing countries. SESI J 2003;13:57–82.
[17] Purohit P, Kandpal TC. Solar photovoltaic pumping in India: a financial evaluation. Proceedings of the ISES solar world congress, Göteborg, Sweden; 2003.
[18] Purohit P, Kandpal TC. Techno-economic evaluation of water pumping windmills in India. Int J Global Energy Issues 2004; in press.
[19] Singh G. Energy input in agricultural production in India. Inst Engrs (India) J-Agric 1997;77:29–36.
[20] Moulik TK, Dholakia BH, Shukla PR. Energy demand for agriculture in India. New Delhi: Oxford/IBH Publishing; 1991.
[21] UNDP. Global windpump evaluation programme: country study on India-preparatory phase. World Bank and United Nations Development Programme, Amersfoort; 1987.
[22] Kandpal TC, Garg HP. Financial evaluation of renewable energy technologies. New Delhi: Macmillan India; 2003.
[23] Purohit P, Kumar A, Kandpal TC. Potential of CO_2 emissions mitigation using renewable energy technologies for domestic cooking in India. Int J Ambient Energy 2002;23:127–35.
[24] Purohit P, Kumar A, Rana S, Kandpal TC. Using renewable energy technologies for domestic cooking in India: a methodology for potential estimation. Renew Energy 2002;26:235–46.
[25] Kumar A, Purohit P, Rana S, Kandpal TC. An approach to the estimation of value of agricultural residues used as biofuels. Biomass Bioenergy 2002;22:195–203.